Robert L. Bates

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THE JOURNAL OF GEOLOGICAL EDUCATION

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All persons interested in geological education are invited to contribute. Manuscripts should be addressed to the Editor at Appleton, Wisconsin. Brief comments and discussion are also welcome and will be given space so far as practicable.

THE ASSOCIATION OF GEOLOGY TEACHERS

The Association of Geology Teachers was founded in May 1938 by a small group in the Middle West. Since its founding it has expanded considerably in the central states, and recently an Eastern Division was organized. Other divisions are planned on a regional basis with a maximum distance between members of 500 miles.

The purpose of the Association is set forth in its constitution: "The Association shall endeavor to foster unity and cooperation among the teachers of the earth sciences, and to promote high standards of instruction in this field."

The Association holds an annual meeting each spring. Sessions are devoted to the discussion of effective teaching methods in some phase of earth science. The program also generally includes an inspection of teaching facilities at the host institution and sometimes a local field excursion.

For the benefit of its members and of the teaching profession the Association has published a frequently-revised "Directory of Geology Departments" and an annual "Interdepartmental Newsletter". Minutes and important papers of the annual meetings have been published in the Association "Proceedings".

Anyone engaged in the teaching of some aspect of earth science is eligible for membership. Applications should be addressed to the Secretary. Membership is confirmed by a two-thirds vote at the annual meeting.

Paul R. Shaffer

President

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GEOLOGICAL MINERALOGY

Chalmer J. Roy
Iowa State College

The title I have chosen is borrowed from Dr. Landes[1], who used it for his presidential address to the Mineralogical Society of America a few years ago. In thus borrowing the title I am assured that, as a fool, I am not rushing in where the angels fear to tread. Whatever acknowledgments and apologies are due the previous author are hereby extended.

In spite of the paper by Landes and a few (too few) others, there seems to be a general lack of appreciation for what is meant by "Geological Mineralogy." Having discussed the matter with a number of mineralogists and a number of geologists I can report two general reactions. The mineralogists seem to agree that the study of minerals in the traditional descriptive fashion is a highly desirable end in itself and should not be prostituted for utilitarian purposes. The geologists seem to think of mineralogy only as a course which was required in their college curriculum, from which they gained little to aid them in their thinking on practical problems in petrology and the genesis of mineral deposits. There is much to be said in favor of the opinions of each group, and I find myself in agreement with both. If, then, there is a problem, what is it?

In concluding his paper Landes says, "Let there be more geological mineralogists! The only requirements,

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[1]Landes, K. K., "Geological Mineralogy," American Mineralogist, vol. 31 (1946), pp. 131-134.

outside of educational background, are a prodigious curiosity, a vivid imagination, and a thick skin." Almost hidden here, in my opinion, is the problem and the bottleneck to the production of more geological mineralogists. The crux of the matter is in the "educational background." The standard course in mineralogy, judging from the texts available, is a descriptive and determinative study. There is very little or no information on the origin of minerals and their physico-chemical and genetic relationships—much less anything about the geologic significance of their occurrence. The only attention given to occurrence in fact is a listing of localities where crystal specimens have been (but not necessarily may be) found.

If one recalls that most geologists have only one course in mineralogy, is it any wonder that they fail to see the minerals because of the pegmatite? This situation is as needless as it is regrettable because the solution is so simple.

Of all the students who take the conventional course in mineralogy I dare say that much less than one percent ever become mineralogists in any sense of the word. That this may be due to the "old fashioned" law of supply and demand, which still holds for geologists and mineralogists, does not alter the facts one bit. What we need is a reorganization of our instruction in mineralogy. If this can be done properly it will greatly increase the opportunities in mineralogy, teach our students some of the chemistry they need to know, facilitate critical observation and effective analysis by geologists, and, in brief, produce the geological mineralogists for Dr. Landes.

Such a reorganization of our instruction must begin with the undergraduate course in mineralogy. The first prerequisite is a text in geological mineralogy. Although I have no intention of writing such a book, even if I could, I see reason to hope that it will be made available. Until that happy day arrives let me make some suggestions about its content and give a

general outline of my own efforts to accomplish the same purpose using available texts.

In any text on geological mineralogy the overall emphasis would be on the minerals and mineral groups of general geologic significance. The major considerations regarding these minerals would be their (1) origin, (2) physico-chemical relationships, and (3) paragenesis. Since geological mineralogists will work mainly with mineral aggregates in which true crystals are rare or absent, the subject of crystallography should be reduced to proper proportion. Determinative tests, procedures, and tables should be placed together at the end of the book and not scattered here and there as in most of our present texts.

Crystallography, with emphasis on crystalline structure and its significance in minerals, should probably come first. A general summary of the crystal systems, crystal description, and symmetry should be included. This, with a moderate amount of laboratory work with crystals and crystal models including some simple exercises in orthographic drawing, will impart sufficient practical information. The core and bulk of the text would be devoted to a discussion of minerals covering the major considerations listed in the paragraph above. The important rock-forming minerals should come first, followed by those of economic and lesser geologic significance. This means that the silicates would come first, and I think rightly so. A good grounding in silicate chemistry is basic to any significant geologic thinking, and to omit it in our mineralogy courses is little short of tragic. Equilibrium relationships in the feldspars and feldspathoids, and between the feldspars and other silicate groups, are certainly a part of basic silicate chemistry. The silicates should be followed by the carbonates, sulfates, haloids, phosphates, and oxides in about that order. The details of economic minerals could well be left to courses in economic geology if time and space prevent their consideration in the first course in mineralogy.

It is perhaps appropriate to indicate some of the specific deficiencies of existing mineralogy texts. The major deficiency is of course the lack of any serious treatment of the origin of minerals. This may include the matter of paragenesis, which was stressed by Landes in his paper as an important part of geological mineralogy. Closely related is the subject of physico-chemical relationships, which are considered in only one of the standard texts. In short, the descriptive-determinative approach, however desirable for the sake of mineralogy, is wholly inappropriate for geological mineralogy. However, one can find reason to deplore standard texts even in their descriptive stronghold. The outstanding omission is an adequate treatment of the clay minerals. No one can seriously question the importance of this group, and it should receive succinct but adequate treatment. Try to find out something about glauconite from standard texts? One text has nothing; another observes that it "occurs in green pellets" and is "similar to biotite" in composition; one lists it under saponite; and one gives it a brief but fair description. Other examples will occur to most readers.

The comments above will indicate the general outline of a first course in mineralogy which I try to teach. The limitations include, of course, my deficiencies through not being a mineralogist, but I like to feel that the absence of an appropriate and adequate text is also a factor. The general sequence of subject matter in the course is as follows:

Introduction. A brief statement of apologetics for geological mineralogy.

Crystallography. Lectures, laboratory, and selected text readings to cover a practical knowledge of the subject. Emphasis is on crystalline structure, which is equally important in anhedra and euhedra. Miller indices are explained first in relation to fundamental lattice arrangements and then with respect to crystallographic axes and axial ratios. This, combined with some crystal drawing,

gives the student a practical knowledge of the subject sufficient to read mineral descriptions and to recognize crystals, determine the system to which they belong, and identify at least the more common forms.

Minerals. Lectures on physical chemistry of mineral groups including selected equilibrium diagrams and their geologic significance. Text assignments cover descriptive material wherever possible. The sequence starts with the silicates and continues through the other rock-forming groups to economic and incidental ones. The silicates, including the clay minerals, receive major attention and a greater portion of the available time. Mineral origins--such as magmatic, late magmatic, hydrothermal, sedimentary, metasomatic, etc.--are discussed in connection with appropriate groups. Paragenesis is also considered but time does not permit an adequate treatment.

Laboratory. The early laboratory periods are devoted to crystallography and the remainder to determinative work. Blowpipe and chemical tests are included but it is not a course in blowpipe analysis. The ideal arrangement is to spend the latter part of the laboratory on the simpler optical tests but in recent years expanded enrollment and low microscope supply have prevented this. Previous experience, however, has demonstrated that this is not only a desirable feature of the course but entirely feasible. Obviously, no attempt is made to cover optical theory, which is unnecessary anyway.

As with any other course the results are not wholly satisfactory. The principal benefit is realized in courses in petrology and economic geology where the background gained is especially valuable. That this approach is not completely un-, or anti-, mineralogic is indicated by the fact that at least one former student is well on his way to a professional career in mineralogy.

For anyone who wishes to try such a plan I suggest the following as excellent sources of geological mineralogy:

Crystallography. Many excellent ideas may be obtained from the book "Chemical Crystallography" by C. W. Bunn, published by the Oxford University Press, 1946.

Silicates. An excellent summary of silicate chemistry is to be found in the new book "Introduction to Theoretical Igneous Petrology" by Ernest Wahlstrom, Wiley and Sons, 1950. In fact, Part I of this book is geological mineralogy at its best. For additional silicate chemistry and the origin of minerals during metamorphism, Chapters II, IV, VII, and VIII of "Evolution of the Metamorphic Rocks" by Francis J. Turner, Memoir 30 of the Geological Society of America, are excellent. Excellent summaries of the clay minerals may be found in papers by Ralph E. Grim, Journal of Geology, vol. 50 (1943), p. 225, and by Walter D. Keller, Encyclopedia of Chemical Technology, vol. 4 (1949), p. 24.

Sedimentary minerals. The geological mineralogy of the carbonates, sulfates, haloids, and phosphates, has been sadly neglected. General summaries with numerous references are found in "Sedimentary Rocks" by F. J. Pettijohn, Harpers, 1949, and in "Geochemistry" by K. Rankama and Th. G. Sahama, University of Chicago Press, 1950.

Economic minerals. There is an abundant literature on the origin and geology of the ore, and other economic, minerals from which material may be obtained. Excellent summaries of hydrothermal processes and effects are available in texts on economic geology. Careful search and judicious selection will provide suitable and adequate material.

Paragenesis. Here again there is no summary of information made to order, but the literature on pegmatites, mineral deposits, and petrology will supply an abundance of significant data. The best course in mineralogy I ever had was devoted entirely

to paragenesis, mainly of the pegmatites. It is not too late for my professor, a mineralogist without peer, to write a book on the subject.

Optical determination. An excellent cook-book technique is outlined in a paper by Phillip West. "Polarized Light Microscopy," published in the Chemist Analyst, vols. 34 (1945), and 35 (1946). Reprints have been available from the J. T. Baker Chemical Co. Phillipsburg, N. J. Although only fifteen pages in length, it presents a determinative procedure which can be followed with a minimum of instruction and without a knowledge of optical theory.

I have been told by mineralogists whom I respect most highly that such a course is radical, impractical, and even impossible; and some geologists agree. But here, as in actuality, I'm from Missouri; and having been shown, I prefer to agree with those of the minority who approve. In fact I am not sure but that this type of course is more common than indicated by college catalog descriptions or textbook adoptions.

MINERALOGY FOR EMBRYONIC PROFESSIONAL GEOLOGISTS

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The title composed of polysyllables means to exclude the teaching of mineralogy as a part of so-called general education, or of adult or other non-professional education (including instruction for amateurs). There is meant to be no implication that mineralogical training in these several aspects is something completely foreign to the subject under discussion.

With the field thus narrowed to what is embraced by the title, further qualification is still necessary. Let us assume we are not dealing with a group of students who are interested solely in becoming mechanical technicians. Let us shoot for those minds in our group which inhabit individuals who are potential discoverers, those who get excited by finding something new whether in theory or practice, and who are willing to do the necessary hard work to find out something worthwhile.

We will thus keep our training time in mineralogy to a minimum because our students want and need education in many other geological and allied fields. They also require time for their own projects or research. The writer has in mind about one third of a student's time over an eleven to twelve week interval, a total of something like 175 hours. It is assumed that the same amount of time has been given to training in "mineralogical" crystallography (American Mineralogist, vol. 34, 1949, pp. 289-290) immediately preceding.

The objectives of such a course may be summarized as follows:

1. Sight recognition of 50 to 100 common minerals.
2. A modicum of proficiency with determinative techniques.
3. Knowledge of a genetic classification of minerals with common examples in each category.
4. Fundamentals of the crystal chemistry of each major class of minerals. Relationship between crystallochemical principles and paragenesis of minerals.

In what follows a paragraph or two is devoted to each of these four topics. It will be noted that the laboratory work covers topics 1 and 2; while class, library, and problem work cover topics 3 and 4.

1. Sight recognition. Sight recognition of the common minerals means that these in their several varieties have turned up repeatedly in the laboratory as unknowns. Cleavage, fracture, hardness, gravity, streak, color, luster, possibly fusibility, and appearance under a hand lens are learned for these minerals; also the variations of these properties among different samples of a single species. Laboratory study of these minerals is tied in with the class work since they are taken as the major examples illustrating the principles covered in topics 3 and 4. However, one need not hesitate to drag a relatively rare mineral (or even a laboratory product) into the class discussion to illustrate a principle.

2. Determinative techniques. It is emphasized that the laboratory work should be intelligent; therefore avoid always using the same tables to determine an unknown. First examine each specimen to note in particular any unusual and highly diagnostic (i.e., rare or even unique) characteristics that will aid in rapid determination. Then use that determinative table (or set of cards) which best fits the specimen. Each student may be supplied with a sheet indexing the

available determinative tables according to the first determinative property used in each table. The sequence in which other properties are used is also given. Such a sheet appears as Table 1 at the end of this paper. Books and periodicals containing the tables referred to are placed on a shelf in the laboratory.

The use of the blowpipe is soft-pedaled. A great amount of time can be wasted with this instrument by the beginner. It is not denied that the expert becomes very clever with it, and of course it may be quite valuable to the metalliferous economic geologist, but let such people acquire their proficiency later. A candle, forceps, and blowpipe are, however, useful to test fusibility (often quite diagnostic, as with lepidolite, amblygonite) and possibly volatility, decrepitation, etc. But don't turn the laboratory into something that should be in chemistry.

On the other hand, considerable emphasis is placed on the ability to determine the optical properties of grains in immersion liquids with the polarizing microscope. This is the tool par excellence of the geologist. It can be used with most of his minerals. It doesn't require anything like the cleanliness of even qualitative chemical analysis to give the index of refraction of a mineral with an accuracy of ± 0.002 with white light. It can and does go into the field. Microscope work in mineralogy is fine training for later work with thin-sections of rocks, where emphasis should not have to be on determination, but on textural and structural relations. It convinces the embryo scientist that geologists can make measurements, can become quantitative; and all this with a tool that is peculiarly theirs, although the chemist and biologist show increasing interest in it. The young geologist is not crushed by the knowledge that there are 1500 or 2000 minerals and that he "knows" only 100 (or 500) of them. He realizes he can determine almost any fresh non-opaque mineral in short order if its properties are

correctly given in U.S.G.S. Bulletin 848.

What about the opaques? Only twenty-five per cent of all minerals are opaque, and probably not over one per cent of the skin of the lithosphere is composed of opaques. Moreover, the microscopical determinative technique for opaques is relatively complex. X-ray diffraction patterns are often desirable or essential. Therefore, let such training wait for more specialized courses. While an occasional former student may tell me he hasn't used a polarizing microscope since leaving school, this says nothing against the tool. It means simply that such a chap has "gone administrative" or he is likely passing up a good bet to help him in his professional work. At the very least his training should have taught him how to handle and understand one modern instrument (Compare the analytical balance of the chemist.)

3. Genetic classification. Only brief suggestions can be given covering the ground of genetic mineralogy, crystal chemistry, and paragenetic relations, since the writer has this material distributed through two "volumes" of lecture notes. Certainly genetic mineralogy at the level of the beginning mineralogy course seems to be in a sad state, judging by the treatment of this subject in the more widely-used textbooks. A notable exception is the 1950 edition of B. G. Escher "Algemene Mineralogie en Kristallografie." Chapter III of Tarr's "Introductory Economic Geology" offers perhaps the best readily available single reference, but of course this is written for a different group of students than we have in mind here. The old (1915) Wherry and Gordon genetic classification (See pp. 11-22 of S. G. Gordon "Mineralogy of Pennsylvania," 1922) is still a valuable one, though now in need of revision. P. Niggli ("Tabellen zur allgemeinen and speziellen Mineralogie," 1927, pp. 212-224) lists the more important minerals found in each of ten genetic categories. The writer lectures on the principles of this subject for about two weeks, after devoting one

week to physical properties and determinative mineralogy. He uses approximately the classification shown in Table 2, at the end of this paper. Very shortly students learn to refer to a given mineral occurrence by its corresponding number in the table. Such numbers are valuable to put in columnar lists of mineral properties and characteristics. In discussing supergene deposits some attention is paid to colloid processes and products, including pseudomorphs. Of course these processes are not by any means limited to such deposits.

4. Crystal chemistry. The broad principles as well as the techniques of crystal chemistry having been covered in earlier work, the remaining lectures of the mineralogy course are what would once have been devoted to descriptive mineralogy. The writer eschews such lectures as far as possible, devoting major efforts to descriptive crystal chemistry and paragenesis. Definite mineral suites occur as such because that is the way nature puts together a limited number of kinds of atoms existing in a reasonably fixed quantitative relationship under a particular pressure-temperature environment (in relatively rare cases influenced by living organisms.) What are the "laws" of mineral composition? What is known of them? What is left to discover? One may use Bragg's "Atomic Structure of Minerals" (1937), Evans' "Crystal Chemistry" (1939), and Wells' "Structural Inorganic Chemistry" (1945)—an English triumvirate—, along with many individual contributions, to get one side of the picture. Part I of H. Strunz "Mineralogische Tabellen" (1949) should also be included here. Crystal structure models of both packing (American Mineralogist vol. 21, 1936, pp. 150-172) and nuclear (Ibid., vol. 22, 1937, pp. 268-278) types should be on hand.

But where will one learn of genesis, and particularly paragenesis, and tie data from these fields in with crystal chemistry? The only reasonably complete source known to me is F. Angel and R. Scharizer "Grundriss der

Mineralparagenese" (1932). A wealth of such material is here available. Outside of this, one is dependent in the main on technical contributions in the journals and allied sources, and many of these are of course quite limited or specialized in scope.

Table 1. Index to determinative tables.

Cleavage
- Krumbein (1930) - v,(IV) - Luster, miscellaneous.
- Rogers (1937) - 563,(574) - Hardness, sp. G.
- Seaman (1935) - 3,(18-31) - Lists hardness and sp. G.
- Winchell (1942) - 491 - Luster, hardness.

Color
- Graves (1947) - 43 - Streak, luster, cleavage, water, hardness.
- Kraus and Hunt (1911) - 14,15 - Streak, hardness. A brief form of this table is in the "Mineralogy" (1936), 454-455.

Crystal angles
- Goldschmidt and Gordon (1928).

Crystal habit
- Dana's "Textbook" (1932) - 817-818 - Crystal system, luster.
- Krumbein (1930) - v,(III) - Luster, miscellaneous.
- Rogers (1937) - 563,(564) - Miscellaneous.
- Seaman (1935) - 3,(32-41) - Crystal system, hardness, sp. G.

Crystal system
- Dana's "Textbook" (1932) - 813 - Luster, sp. G., hardness.
- Niggli (1927) - xi-xiii,(39-186) - Habit, luster.

Geologic occurrence
- Gordon (1922) - 16-22.
- Niggli (1927) - 212-214.

Hardness
- Fuchs-Brauns (1921) - 105 - Luster, color or streak.
- Rosenholtz and Smith (1931) - 54 - sp. G.
- Winchell (1942) - 469 - Streak, sp. G.

Luster
Crosby (1895) - 25 - Color or streak, hardness.
Dana's "Manual" (1941) - 415 - Streak, hardness, cleavage.
Davison (1937) - 30 - (Streak), hardness.
English (1934) - 269 - Hardness, color.
Frazer-Weisbach (1891) - x - Color or streak, hardness.
Niggli (1927) - xiii,(187-206) - Color, hardness.
Phillips (1912) - 595 - Color or streak, hardness.
Massive minerals only (no characteristic structure or cleavage)
Krumbein (1930) - v,(V,VI) - Luster, streak, miscellaneous.
Rogers (1937) - 564,(579) - Color, hardness.
Seaman (1935) - 3,(42-49) - Luster, color or streak.
Sectile minerals
Seaman (1935) - 46.
Specific gravity
Beringer (1931) - 13 - Hardness.
Niggli (1927) - 210 - Crystal system, luster.
Rosenholtz and Smith (1931) - 54 - Hardness.
O. C. Smith (1940) - 75 - Hardness. See also Smith (1946) - 171.
Streak
Eakle (1938) - 9 - Color, hardness.
Lewis (1931) - 20 - Color, (cleavage), hardness.
Niggli (1927) - 207 - Luster, hardness.
Winchell (1942) - 436 - sp. G.
Structure (not purely massive)
Graves (1947) - 152,158,162.
Krumbein (1930) - v,(I,II) - Luster, streak and miscellaneous.
Niggli (1927) - 210-212 - Crystal system.
Rogers (1937) - 563,(569) - Hardness, sp. G.
Taste
Moses and Parsons (1916) - 594-595.
Phillips (1912) - 635-640.
Seaman (1935) - 46.

Table 2
Outline of a genetic classification of minerals.

Igneous rocks.

1. Persilicic ("acid") magmatic.
   Granitic type. 1a may be used for alkalic, and 1m for mediosilicic.
2. Subsilicic ("basic") magmatic.
   Gabbroic type. 2a may be used for alkalic; 2u for ultrabasic.
3. Pegmatites.
   Granitic type. 3a, 3m, 3s (subsilicic), and 3u may be used for special types. Note this heading refers strictly to that portion of a pegmatite formed in the pyrogenic stage (cf. S. Dak. Geol. Surv. Rept. of Invest. No. 50, 1945, pp. 7-20.) Associated hydrothermal or supergene deposits fit under 6,7,8 or under 3h or 3w (weathered pegmatite).

Metamorphic deposits.

4. Contact (tactites, skarns, etc.)
   One may use 4h for hydrothermal metamorphs, if not 6 or 7, and 4d for deuteric minerals.
5. Pressure.
   This refers to the minerals of the lineated (amphibole) or platy (micaceous) metamorphs (schists and also many gneisses). One may use 5c (compression, as opposed to stress) to single out the granoblasts ("three-dimensional" porphyroblasts) such as staurolite and some garnets. Unoriented pyrite hexahedra in a gneiss may be put under 6,7, or 8.

Hydrothermal deposits, whether fissure-fillings or replacements.

6. Hypothermal.
7. Mesothermal and epithermal.
   If desired, mesothermal and epithermal may be distinguished as 7m and 7e. The category may also include:
   - 7f. Fumarolic deposits.
   - 7s. Hot springs deposits.
   - 7z. The zeolites.

Supergene deposits (meteoric waters and weathering).

8. Vein deposits, cave deposits, etc.
   8s may be used for the secondary enrichment zone; 8o for the oxidized zone; etc.
9. Minerals of the sedimentary rocks.
   - 9b. Bioliths--as diatomites, coals, some limestones (chalks), and iron ores.
   - 9c. Chemical precipitates--as possibly some limestones and iron ores.
   - 9e. Evaporites--as halite, gypsum, anhydrite, etc.
   - 9f. Fragmental--as clastic and placer deposits, some clays, and some volcanic ash.
   - 9r. Residuals--as some clays, some phosphate rocks.

AN OUTLINE OF A COURSE IN ELEMENTARY MINERALOGY

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One of the most important tasks of an instructor in elementary mineralogy, if not the most important one, is to make the course interesting to his students. The best guarantee of his success in this vital respect is a spontaneous enthusiasm for his subject. Minerals in the hand specimen are aesthetically satisfying; their identification constitutes a stimulating challenge to the student's ingenuity; and the lore of their occurrence, extraction, and use is a fascinating human document. Hence, to win the students' sympathy and interest, it is only necessary for the instructor to avoid obscuring the intrinsic attractiveness of the study by laborious and stuffy pedagogy. At most institutions courses in mineralogy are offered by the Department of Geology and majors in geology make up the bulk of the enrollment. Many a good student has been attracted to the field by a fascinating course in elementary geology, only to be turned away by a poor course in mineralogy. Elementary mineralogy can be made interesting without sacrificing quality; indeed, the quality can be enhanced by so doing.

Some schools, I believe, try to teach too much in an elementary course and the net result is that the student learns very little about a great deal. Moreover under such conditions there is no time to make brief excursions into other fields to enliven the lectures. For an adequate introduction to the field, a beginning course should, if possible, extend throughout the academic year. This allows several weeks for the presentation of the fundamentals of crystallography excluding optical and X-ray crystallography. Approximately the same amount of time can be devoted to e

discussion of both the physical and chemical properties of minerals. Such a time schedule leaves a minimum of half of the academic year for descriptive mineralogy.

The order in which the various branches of mineralogy are considered in most American textbooks is the same. Crystallography is followed by physical mineralogy, chemical mineralogy, and descriptive mineralogy. Although this is a very logical order of procedure, I believe that it is unnecessary to make any sharp division, for all branches are so closely related to one another. Wherever possible the instructor should cut across these boundaries to integrate the science into a unified whole. This is particularly important in the introduction of material from the related fields of chemistry and physics in order to demonstrate to the student the essential continuity of mineralogy with the other physical and natural sciences.

Crystallography. In one way it is unfortunate that crystallography is considered first in a mineralogy course. For many students it is the least interesting part and they may thus get off to a bad start. To those of my students who have a difficult time thinking in three dimensions and who therefore begin to rebel against crystallography, I point out that they should consider crystallography not an end in itself but a means to an end. Because the sight recognition of crystal forms and habits is a powerful means of mineral identification, it is a necessary part of mineralogy. An hour spent in the study of crystallography may save the student two hours later in the term, when he can make an immediate identification on the basis of crystallography. Of the various tools used in mineral identification, crystallography gives, so to speak, the most for the money. If inspection of a specimen shows it to be made up of tetragonal crystals, the field is at once limited to minerals crystallizing in this system and usually some other simple test will furnish positive identification. For some minerals the habit is so characteristic that it alone is sufficient. These arguments generally suffice to quiet the doubts

of students, but the genuine incapacity of many persons for three-dimensional visualization can only be overcome, if at all, by patient guidance in the laboratory. Every possible visual teaching aid should be made use of in this connection. The use of zonal relations has proved particularly effective. The use of zone formulas and zonal diagrams is also very helpful in the rather dismal business of drill on Miller indices.

A lecture, or even half a lecture, on the history of crystallography is a welcome change to the students from the normal routine. In such a lecture one can touch on early ideas regarding crystal structure and on the development of the laws of rational indices and the constancy of interfacial angles, and can show how beautifully these laws fit in with the present day concept of the unit cell. Also, mention can be made of the development of the reflecting goniometer, progress in the study of the optical properties of crystals, and the use of X-rays in crystal study. This is also a favorable time to introduce some of the generalizations of crystal chemistry, which give the students a feeling of the firm foundation in reality of the rather idealized and formal subject matter of geometrical crystallography. Brief as it must be, a presentation of this nature will inspire some students to go on with more advanced work in crystallography and mineralogy.

Although crystallography is usually presented at the beginning of the mineralogy course, one should not plunge into it without at least some brief introduction to the subject as a whole. A well-known mineralogist at a large university was known year after year to greet his students at his first lecture with some such statement as, "The forms of the isometric system are built about three axes, equal in length and mutually at right angles." Needless to say, the students were bewildered at the start, a state from which only a few completely recovered. No matter how limited the time for the course, it is important that the first lecture be of a general nature. One can give something of the occurrence and association of minerals, the relation of

mineralogy to geology and chemistry, the methods of the mineralogist, and the importance of minerals to our civilization. If large mineral specimens can be placed on the lecture table, they serve better than words to capture the attention and interest of the students. A further device that is particularly effective is the inclusion in the first lecture of some remarks on mineralogical "current events" —the discovery during the summer of new localities, the acquisition by the university of new specimens (which may be advantageously displayed), or the use or development of new techniques or methods of a sufficiently spectacular character. This type of introduction emphasizes the dynamic character of natural science and dispels the all too frequent misconception that mineralogy is a "fossilized" science.

Physical Properties. The dependence of many of the physical properties of minerals upon their crystal structure offers an excellent bridge between crystallography and physical properties. The properties of cleavage, hardness, light absorption, and conductivity of electricity and heat are all vectorial and thus directly related to crystal structure. As far as possible, demonstrations should be carried out showing the directional nature of these properties.

All the physical properties can be advantageously presented by means of demonstrations. In addition to illustrating the use of the Jolly balance and beam balance, it is most effective to show how to obtain specific gravity by suspension in bromoform. Considerably greater amplification than is customary of the practical aspects of those properties which are of commercial or technical importance, such as piezoelectricity, pyroelectricity, phosphorescence, etc., is welcome to the students and helps convince them of the immediate applicability of the science to practical problems. Nothing can be more dramatically demonstrated than fluorescence with a well-chosen exhibit of fluorescent minerals.

Chemical Properties. If a course in college chemistry is not a prerequisite for mineralogy, the instructor should not assume too great a knowledge of chemistry but should review certain fundamental aspects. The interdependence of crystallography and chemistry should be emphasized. A discussion of the different types of compounds and their chemical bonds serves to illustrate well the close relation between physical, crystallographic, and chemical properties.

Although fixed chemical compositions are given for most minerals, the student should be made aware that many elements are usually present in natural systems. As a result substitution for one element by another is common and the chemical formula generally does not give an exact picture of the composition. It should also be pointed out that there are many pairs or groups of isostructural minerals between which there is complete or limited isomorphism. The criteria for substitution such as atomic radii and valence should be touched upon, and the variation in physical properties with compositional variation should be convincingly demonstrated.

Although the blowpipe is considered by some to be outdated and old fashioned, I am a firm believer in its use as a tool in determinative mineralogy. In using blowpipe tests, one is looking for evidence of the presence of certain elements; they thus serve as a continual reminder to the student of the chemical composition. Moreover, there are certain blowpipe tests that are quick, positive, and easier to make than any other: for example, the charcoal tests for antimony, arsenic, and lead; the plaster tablet tests for molybdenum and bismuth; the flame tests for barium, strontium, lithium, and copper; and the bead tests for manganese, uranium, cobalt, and chromium. Blowpipe methods have the additional advantage that the equipment is inexpensive. It is not bulky and can be easily carried into the field where the only heat needed is a candle flame. If the equipment is available,

spectroscopic and microchemical tests are preferable to the standard wet qualitative procedures, which should be used only as a last resort. The blowpipe still remains the chief tool for chemical mineralogy, but its full value as either a teaching aid or a diagnostic technique can only be realized by direct, competent personal guidance in the laboratory. The method is otherwise likely to be only half-learned, and later in the course completely disregarded.

Descriptive Mineralogy. The laboratory work in descriptive mineralogy is, as in the other branches, of greatest importance. One can talk about minerals for hours but only be seeing them, handling them, and testing them can one actually learn to know them. There is no better way than to go into the field and see them in place. Moreover, when a student has spent half an hour trying to extract a poor crystal from a rock, he has much more respect for the better crystals and specimens he handles in the laboratory.

In a full-year course one can cover between 150 and 175 species. These can be arbitrarily divided into groups, each of which makes a workable unit for study at one time. One scheme that has proven practical is to group the minerals as follows: (1) native elements, sulfides, and sulfosalts; (2) oxides and halides; (3) carbonates, borates, phosphates, sulfates, tungstates, molybdates; (4) silicates. The rock-forming silicates can be taken as a separate group. It is highly desirable that a lecture and a few laboratory periods be devoted to a study of the common rock types in conjunction with the work on the rock-making silicates, particularly if no course in hand-specimen petrography is offered by the department. The first part of the laboratory work on each group (perhaps a week) can profitably be devoted to handling and observing musuem-quality specimens of the different minerals. As many labeled specimens as possible should be made available so that the student can get an idea of the various associations and range in habit and color. Fragments

of the same minerals should also be at hand so that hardness and specific gravity can be determined and blowpipe tests made without damaging the study specimens. Before this part of the laboratory work is begun, the instructor should point out those features of each mineral that are most characteristic, so that the student can watch for them as he handles the specimens. This emphasis on the diagnostic characters may be further encouraged in the laboratory by assisting individual students to prepare for themselves systematic diagnostic tables or keys to the species.

The second part of the laboratory work on a group can consist of a series of trays of unknown specimens. On these the student may make any test he feels is necessary for positive identification. He should be familiar enough with the minerals by this time so that by inspection he can rule out all but two or three. One or two of the properly selected tests should then suffice for identification. If the class is not too large, an oral rather than a written report is more satisfactory. In this way the instructor can learn how the specimens were identified and can ask something of the association, occurrence, uses, etc. In short, he gets a much better idea of the student's grasp of the subject than he does by merely checking off written mineral names against specimens. Short written tests on sight identification of minerals can also be used in an effective manner to supplement the other type. Gaining of speed in sight recognition as opposed to identification may also be encouraged in this way.

The lectures in descriptive mineralogy offer the greatest opportunity to enliven the course. I cannot say that my own lectures are all-absorbing to the students, but I can say that those of my teacher, Professor Palache, were. We cannot all be Palaches, but we can profit by his method of instruction. The factual data are adequately presented in most of the textbooks and little can be added to them in the

lectures. For most minerals, however, Palache could find something that warranted amplification. It may have been one or several of the following:

Genesis and occurrence.
Geological environment.
Mineral association.
Piezoelectricity and uses based on this property.
Isomorphous relations.
Pseudomorphs.
Discovery of the mineral or discovery of an element in a mineral.
Unusual aspects of crystallography.
Description of world-famous localities.
Methods of mining.
Extraction of the useful mineral from its ore.
Methods of synthesis.
Uses of the mineral or the extracted metal.
History.

For example, outlines for lectures on the first two minerals, gold and silver, might be as follows:

Gold

Crystallography:
  Flattened or elongate crystals.
Physical Properties:
  High specific gravity.
  Very malleable.
  Color characteristic but silver makes it lighter.
  Characteristics of "fool's gold"
Distribution and association:
  Veins.
  Placers.
    How placers are found.
    Famous placers: California, Alder Gulch, Klondike, etc.
    Buried placers.
    Hydraulic mining and dredging.

Methods of extracting from ore:
  Amalgamation, cyanide.
Famous mining districts and countries:
  The Rand.
  California.
  Alaska.
  Canada.
Annual production of foremost producing countries.
Uses.

Silver

Crystallography:
  Similar to gold.
Physical properties:
  White but tarnishes quickly.
  Hackly fracture; sectile, malleable.
Occurrence:
  Supergene at many localities.
  Only a few localities are large producers from primary ore.
  Freiburg: early silver production and characteristic mineral association.
  Konigsberg: early mining and present production.
  Cobalt, Ontario: similarity to Freiburg mineral association.
  Association with uranium.
  With native copper at Lake Superior.
  Uses.

The above outlines may appear to emphasize the economic aspects, but it should be remembered that these two minerals are of great economic importance. Moreover, since both silver and gold as metals are familiar to all, their occurrence in the native state is of greatest interest. It is important to give the student something of interest to remember and to which he can link the more factual knowledge. The story of the discovery of gold in California, the gold rush of 1849, the buried placers, hydraulic mining, dredging, and the Mother Lode will be something he will always

remember.

For silver, emphasis can be placed on the early development of the mines at Freiburg and the association of native silver with niccolite, smaltite, cobaltite, and native bismuth. The discovery of niccolite, smaltite, and cobaltite at Cobalt, Ontario, and the prediction that native silver should also be present, gives a graphic illustration of the fact that similar mineral associations are to be found in different parts of the world.

Throughout the course, and particularly in the descriptive mineralogy, one should not lose sight of the fact that mineralogy is a natural science. The increasingly close relationship of the science of mineralogy to physics and chemistry through the media of physical crystallography and crystal chemistry, fields much publicized as a result of their substantial contributions to present day technology, tends to obscure the fundamental difference between the underlying philosophy of mineralogy and that of the physical sciences. This difference arises out of the dominating concern of the mineralogist for the genetic, historical, and economic consequences of his findings, as well as out of his different approach to his sources of information. The court of final appeal in mineralogy is the earth's rocky crust itself, rather than the controlled quantitative experiment performed in the laboratory. Thus the mineralogist is always keenly aware of the tremendous complexity and diversity of the natural universe. This difference is a wholesome one, and has much to offer the student in a philosophical sense. Many students, star-struck by the profound and precise mathematical generalizations of the physical sciences, and awed by their complex technology, find their feet brought gently but firmly back to earth by a well-taught course in mineralogy. This is a proper and worth-while goal, which, if achieved, may make a course in mineralogy valuable to many students not primarily specialists in the earth sciences.

AUTOMATIC TESTING PROGRAM IN MINERALOGY

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Under the Antioch Cooperative Program the academic schedule provides four study periods each year, two of eight weeks and two of twelve. The student group is divided into two sections, each student being enrolled in one eight week and one twelve week period during the year. The division into two sections cuts in half the number of students which would be enrolled in the conventional type of college program and so puts a premium on efficiency of teaching.

Two characteristics of Antioch indicate the direction in which such efficiency can be achieved. There is prevalent an educational philosophy which emphasizes the student's responsibility for learning; formal courses are for guidance and appraisal. The other element is the thoroughgoing honor standard, which applies not only to examinations but to all phases of on-campus and off-campus life. While no claims are made for perfection in the operation of this honor system it does provide the environment in which self-testing can be valid.

The eight week period in Elementary Mineralogy includes the usual introductory study of crystal models and physical and chemical properties. The twelve week period is devoted to the examination and study of mineral specimens. The total number of specimens, estimated at between 600 and 700, covering 130 species, is divided into eight study groups. The groups are kept in labeled drawers and the students study them when they choose.

In the twelve week period one hour a week is scheduled as a class period and is devoted to "helpful

hints" for identification: mineral associations, isomorphic series, polymorphism and so on. A laboratory period is scheduled when the instructor will be in his office to answer questions but this is not regarded as a compulsory study period.

On the assumption that ability in identification is the real test of mineralogic accomplishment, the testing program is entirely identification. When a student feels he has studied a group of specimens sufficiently he goes to a drawer containing the test, numbered to correspond with that group. He takes the test and turns in a slip of paper containing the identifications. It is understood that he is at liberty to use any of the regular methods of determination; he is not to "use the book" or compare with labeled specimens except as a last resort and then he must indicate on his paper what aid he utilized.

The tests are so arranged that the majority of specimens in each test group are the same species as those in the corresponding study group, but in each test after the first there are included some specimens from preceding groups. Because of this constant incentive to review, the study groups have a decreasing number of species in them—that is, the first group has about twice the number that the last group has. The last test covers the last group and all previous groups and constitutes the final examination.

All test results are brought to the instructor, who marks the answers right or wrong in the student's presence and returns the test. All wrong identifications must be restudied until corrected. This gives opportunity for the teacher to check procedures and methods and determine how perceiving and how skillful each student is.

Students appear to like the plan; this year all of them finished well ahead of the time schedule. And as partial evidence of honesty it can be said that no

student had a perfect score and all of them reported that they resorted to aids at one time or another.

It is probable that such a program can work successfully where the enrollment is small enough so that personal acquaintance between teacher and student reinforces the operation of the honor system and where faulty procedures and failures to observe accurately and keenly can be caught informally.

TEACHING PROCEDURE IN UNDERGRADUATE MINERALOGY COURSES

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Undergraduate mineralogy courses at the Michigan College of Mining and Technology are aimed primarily at giving the student a ready method by which almost any mineral may be identified. Cleavage and crystal habit, as observed with the aid of a hand lens, are stressed. Classroom procedure is presented here in some detail.

Each class meets seven hours per week; there are two two-hour laboratory-quiz sessions, two one-hour lectures on the preceding lab-quizzes, and a one-hour general lecture.

The apparatus and texts used are: hand lens (15X triple aplanet preferred), streak plate, magnetized knife, a penny, Dana's "Textbook of Mineralogy", and W. A. Seaman's "Mineral Classification Tables" (now out of print; the writer is revising these tables and at present is using them in mimeographed form).

The first two weeks of the course are devoted to lectures demonstrating various physical properties and acquainting the student with the texts; types of cleavage, hardness, luster; and so forth.

By the third week a routine is worked out, which is thereafter closely adhered to: during the two-hour laboratory-quiz session a student is given a tray of three minerals and is asked to work out the following data for each specimen:

1. Number of cleavages.
2. Perfection of each cleavage.
3. Angles between cleavages.
4. Hardness, and specific gravity if time permits.

At the end of the first hour he is given another tray of three minerals and is asked to repeat the process. Each student works by himself and has his own tools; no communication is permitted. The next day the instructor, having corrected and graded the papers, lectures on the six minerals, showing what the student should have observed and what methods should be used to identify the specimens. Both the lecturer and the students have specimens in their hands while the lecture is in progress.

The next meeting of the class is another lab-quiz period, and the students are again given two trays of three minerals each. The lecture follows on the next day. Thus the procedure is repeated, each time with new minerals to be examined.

This procedure takes up six hours of the week. The seventh hour at the beginning of the course is devoted to general lectures on minerals: their occurrence in nature, their uses, etc. Later in the term orthographic drawings of the orthorhombic, tetragonal, and monoclinic systems are drawn in class. As an out-of-class assignment, each student then draws an example of each system.

The specimens used at the beginning are coarse and homogeneous, but as time goes along smaller and mixed specimens are introduced. At first the student recognizes only the perfect-plus and perfect cleavages. Later the poorer cleavages become familiar to him. There are seven degrees of perfection of cleavages: perfect-plus-plus, perfect-plus, perfect, perfect-minus, distinct-plus, distinct, and distinct-minus. As soon as the student has become familiar with cleavage

fragments, simple crystals are introduced. Later, massive materials are put in the trays.

Thus a program is maintained comprising lab-quiz with a lecture, lab-quiz with a lecture, and a general discussion. At all times the student is working with new material.

Finally, when specimens are presented to the student, he automatically classifies them into one of the three major groups: cleavage fragments, crystal forms, or massive. If the specimen is a cleavage fragment, the number, perfection, and angles of cleavages are described and determined. If it is a crystal form, a sketch is made, the system determined, crystal faces labeled, and cleavages noted. If massive, the luster, streak, hardness, specific gravity, and any other recognizable property are carefully determined. Diagnosing in this manner, the student learns quickly to distinguish minerals first by group classification; then with the aid of other tools he can run down the specific name. Once he gets the name, he is required to record the chemical composition.

The disadvantages of the method used at Michigan Tech are that the student classes must be kept small, the instructor must have a large number of matched specimens, and a great amount of individual instruction is required. Words alone will not help a student see cleavage; the instructor must be present and make sure that the student observes accurately. This is probably the first college course in which the student begins to use solid geometry as a tool. Some students have surprising difficulties. For example, take a barite cleavage fragment. It has two perfect cleavages at 60° to each other and a third perfect-plus cleavage at 90° to the two perfect cleavages. For a student to look at the irregular fragment, count up to six and divide by two, keep track of the perfections of the cleavages and their angular relationship, and visualize the type of a solid they make, is often a major

undertaking.

The major advantage of this type of course is that the student is trained in observation and in coordination. He learns that a mineral can come in any color, that its specific gravity varies, that its hardness changes because of alteration or weathering, but that its cleavage properties and crystal form remain the same. The course is flexible. The number and type of specimens can be adjusted to the students' ability to absorb.

CRYSTALLOGRAPHY IN THE GENERAL MINERALOGY COURSE

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Indiana University

In this article I am concerned with the teaching of crystallography as part of an undergraduate course in mineralogy. In such a course one is generally dealing with a heterogeneous group of students. The majority of the group will comprise geology students for whom this course may be their first and last in crystallography and mineralogy; a moderate percentage will later apply crystallography in the study of optical mineralogy; and a few intend to specialize in mineralogy and may eventually do research work in some branch of crystallography. In addition, the course generally attracts some students in chemistry and physics who wish to learn the essentials of morphological crystallography as a background for the chemistry and physics of the solid state.

The objectives of such a course are as varied as the student body. For most students, the immediate purpose in studying crystallography is to facilitate the identification of minerals by their crystallographic properties. Fundamentally, however, the course is intended to give the student an understanding of the significance of the external form of crystals in relation to internal structure and the manifestations of internal structure such as cleavage, hardness, and twinning. The course must also provide basic knowledge for students who will proceed to advanced work in optical crystallography, X-ray crystallography, crystal chemistry, and crystal physics. All this is to be achieved within the limited time that can be allotted in an already loaded curriculum--generally in ten to twenty lectures and a similar number of laboratory periods.

Crystallography does not come easily to the average student. It requires three-dimensional thinking and all his prior learning experience has been two-dimensional. Few students have even a nodding acquaintance with solid geometry, much less spherical trigonometry. Here we have a mental roadblock which can only be broken down by assiduous working with crystals or crystal models. In teaching crystallography in a general mineralogy course, the best results would presumably be obtained if it were possible to work entirely from natural crystals. This, however, is a counsel of perfection, since sufficient natural crystals of the size, variety, and perfection necessary for the instruction of large classes are generally not obtainable. Crystal models provide an acceptable substitute. A firm in this country now produces a wide range of ceramic crystal models, and the excellent German pearwood models are again available, though at a high price. However, when it is possible, natural crystals should be used.

In the course as taught at Indiana University, we give the students considerable practice in the measurement of natural crystals with the contact goniometer. That is as far as we can carry instruction in goniometry in the course in general mineralogy. For students who want it, a later course in the use of the reflecting goniometer is arranged.

The subject of crystallography can be approached in several ways. The subject may be viewed in its historical development from the discovery of the constancy of interfacial angles by Steno through the enunciation of the law of rational indices by Hauy and the establishment of the thirty-two symmetry classes to the ultimate demonstrations of the regular internal lattice of crystals by X-ray diffraction. Alternatively, one may begin by considering symmetry as a fundamental property of crystals—the basis for the classification of crystals in thirty-two classes—and then proceed to the law of rational indices and the description of

individual crystals. Or again, one may start by considering the crystal as an assemblage of atoms regularly arranged in a three-dimensional lattice. Any crystal face is then a limiting lattice plane, and it is possible to arrive at the law of rational indices directly. Other approaches are also possible, but the above seem most satisfactory. In actual practice, no one approach need be employed exclusively. Each has its advantages, and they are woven together as far as possible. The historical approach is particularly valuable as indicating the way in which the science has advanced. At the same time, the concept of a crystal as a regular arrangement of atoms in a lattice is kept before the student, thus encouraging him to think always of the underlying factors controlling crystal morphology.

At Indiana University the undergraduate course in mineralogy is usually taken in the first semester of the junior year. The course entails two one-hour lectures and two two-hour laboratory periods per week for fourteen weeks of instruction. The course is at present taught in the following manner: one lecture and one laboratory period each week are devoted to crystallography; one lecture and one laboratory period to mineralogy. This arrangement is preferred over an earlier plan in which crystallography was taught during the first half of the semester, mineralogy during the last half. The course begins with a discussion of the nature of a crystal and an outline of the development of ideas from the time of Steno onwards. In this way, symmetry is introduced as a means of classifying crystals, and the evolution of the concept of a crystal as a regular arrangement of atoms in a lattice is brought out. Symmetry is described in terms of planes, rotation axes, and inversion axes, and the relation of a center of symmetry to these elements is pointed out. The derivation of the thirty-two crystal classes is briefly treated. The Hermann-Mauguin notation for the crystal classes is given, as an elegant shorthand for the symmetry of the classes and as a basis for advanced work in X-ray crystallography. Crystal systems are then

introduced as a convenient means of grouping crystal classes. On this basis, seven crystal systems are recognized, the trigonal system being regarded as a system in its own right characterized by the possession of one triad axis, either a rotation or an inversion axis. At this stage, the description of crystal faces in terms of axes, parameters, and indices is introduced. Then follows instruction in the use of the stereographic projection as a means of representing crystals. Considerable time and emphasis is given to the stereographic projection, not only because it is an excellent means of concentrating attention on the fundamentals of crystal morphology-symmetry and interfacial angles, but also because the stereographic projection is essential in advanced phases of geology and this is a good opportunity to make the student conversant with it. After the principles of stereographic projection have been mastered, the final part of the course is concerned with a detailed discussion of the more important crystal classes. At present this discussion follows the usual textbook order, proceeding from the class of highest symmetry, the hexoctahedral, to that of lowest symmetry, the pedial. However, I am inclined to think that the reverse order of treatment would be preferable, both logically and pedagogically.

Each laboratory class is designed to illustrate the subject matter of the previous lecture. The first laboratory exercise is the measurement of interfacial angles with the contact goniometer, incidentally repeating Steno's demonstration of the constancy of interfacial angles of quartz. (Quartz crystals are very suitable for this exercise since they are readily obtainable in a variety of habits.) This is followed by the recognition of symmetry elements in crystal models and the assignment of the models to the crystal classes and systems to which they belong. The student then proceeds to the selection of axes of reference for crystals belonging to different systems, and the indexing of faces. After the foregoing has been mastered, three or four laboratory periods are devoted

to the construction and interpretation of stereographic projections of crystals. The remainder of the semester is devoted to the study of crystals and models belonging to each of the seven systems (generally one laboratory period to each system.)

A major difficulty in presenting an adequate course in crystallography is the lack of a suitable textbook. I recommend "An Introduction to Crystallography" by F. C. Phillips to my students as the most satisfactory book in the field. It contains more material than is covered in the course which I have outlined, but students who proceed to more advanced work will find the additional material useful. Phillips' book also has a good deal of interesting matter on the history of crystallography. Of the textbooks of mineralogy, those of Dana-Ford ("Textbook of Mineralogy"); Kraus, Hunt, and Ramsdell ("Mineralogy"); and Rogers ("Introduction to the Study of Minerals") have fairly extensive sections on crystallography. Each has its good points but none is entirely adequate. I do not know of any textbook which gives a satisfactory derivation of the thrity-two crystal classes. For this, two useful references are C. K. Swartz, Bull. Geol. Socy. America vol. 20 (1909), pp. 369-398, and J. D. H. Donnay, University of Toronto Studies, Geological Series No. 47 (1942), pp. 33-51. Swartz also gives a useful historical review on the application of symmetry in the classification of crystals.

The preceding program is presented not with any idea that it is the "best" method of presenting the subject. There is no one best method, since too many variables are involved: the institution, the teacher, the time available, the students. This is not to say, however, that one method is as good as any other. The course as outlined has been evolved over a period of years and will certainly be changed as experience indicates improvements. This article is an account of how the subject is taught in one institution. It is presented

in the hope of stimulating discussion and an interchange of ideas and experience in the teaching of a subject important both for its content and for its insistence on precise thinking.

MINERALOGY AND CRYSTALLOGRAPHY IN ENGINEERING CURRICULA

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Minerals and rocks probably have been part of man's world since his very beginning. He found use for them as tools and weapons and came to distinguish those which made good knives and arrows from those which did not. He learned too that some could be struck to yield glowing embers by means of which he could kindle a fire to keep him warm and render his food more palatable. He came to recognize the beauty of stones and appeased his vanity in self-adornment. He found that other men, equally vain and envious, were willing to accept such baubles in exchange for weapons or wives, food or favors. Not being content with things as they were, man discovered ways of converting natural things into others of greater utility. He shaped clays to form bowls and learned to dry and bake them so that they would hold water. He converted minerals to metals by means of his fire. He became characterized by his inventive ability.

By the time man began to organize his knowledge of minerals they were widely used. Thus mineralogy began as a practical science. It has long been considered part of any curriculum in mining or metallurgy. Crystallography, in contrast, developed as a classical science. Undoubtedly man was early impressed by glistening crystal faces and regularity of crystal form, but these characteristics were of little practical value. They stirred his imagination and caused him to speculate concerning their nature, but not until the present century did he find out what a crystal really is, and only within the last twenty-five years has man put crystals to much use. Within this twenty-five years, however, the applications of crystallography have become diverse and manifold.

Our modern elementary textbooks dealing with mineralogy and crystallography tend to follow the development of the sciences. Crystallography is treated in a classical manner. Emphasis is placed on crystallographic laws, crystal classification, and crystal forms, with scarcely a hint that crystallography is useful. Mineralogy is presented largely as a catalog of selected minerals, which commonly are regrouped in a set of determinative tables. This frequently is the only application which is stressed. Teachers of mineralogy and crystallography are prone to conduct their classes along the same traditional lines instead of modernizing the subjects and instilling enthusiasm by emphasizing applications, genetic significance, and relationships. The importance of mineralogy and crystallography to the geologist, the mining engineer, and the ore dresser may be self-evident. The beginning student should be made cognizant too of the importance of these subjects to the ceramist, the chemist, the soil scientist, the physical metallurgist, the civil engineer, the paint manufacturer, the communications expert, the designer of highways and foundations, and others.

Mineralogy and crystallography are living and growing useful sciences. They ought to be treated as such. So often the uses of minerals, their associations, and their modes of occurrence are treated too briefly or relegated to an obscure section of our textbooks. We spend so much time teaching students how to identify minerals that we have little left to discuss those properties upon which the uses of the minerals depend. The student is apt to learn the structure, cleavage, and hardness of phlogopite without knowing anything about its dielectric constant or without realizing that it is a combination of these properties which makes it useful to the electrical industry. We are likely to spend so much time on crystal classification that we scarcely mention an important concept likely to be new to the student--the vectorial character of properties in crystalline materials. In chemistry and physics the student has become familiar with the general chemical and physical properties of materials, but in

crystallography he should come to realize that the properties of crystalline materials depend, not only upon the properties of the constituent particles, but also upon their mode of union, their arrangement. The student is apt to learn the common crystal forms of diamond and its Mohs hardness, but he is not so likely to learn that all surfaces of diamond are not equally hard, nor that the octahedral surfaces of diamond are the hardest surfaces known to man, nor that this fact coupled with the fortunate octahedral cleavage permits diamond dust to be used as an abrasive in cutting all but octahedral planes of diamond.

By stressing the practical phases of mineralogy and crystallography, the writer has been able to develop student interest beyond that given by a more classical treatment. These subjects have their cultural aspects as well. For those who are not going to deal with minerals and crystals in a practical way, a course in elementary mineralogy covering elementary crystallography gives a general knowledge of a very important part of man's world. No one is wholly independent of his mineral environment. Most of us are more dependent upon it than we realize. Since mineralogy gives us a better understanding of the inorganic phase of our environment it adds to our culture. There are some who seem to think that practical subjects are not cultural, but the more we know the more cultured we become. In our modern age, culture must consist of a combination of the practical and the aesthetic. Knowledge in any field enhances our enjoyment of life. Mineralogy and crystallography teachers should not permit this fact to be overlooked by those who design college curricula. The recent great rise of mineralogy as a hobby, and the enthusiasm with which it is pursued by those who have taken it up in this manner, would seem to indicate that the general public has accepted its cultural value. At least, these people have found a way to get more enjoyment out of life.

In spite of the practical and cultural aspects of mineralogy and crystallography, there has been a

tendency in engineering curricula to displace these subjects in whole or in part by others considered more essential. We still are trying to teach in four years, not only what was taught at the beginning of the century, but also all that has been learned since. Selection of subjects to be included in a modern curriculum of necessity often reaches the stage of a major amputation. Specialization replaces broad education. Mineralogy and crystallography may be losing their places in modern curricula because those who design these curricula either have not been exposed to these subjects or have not taken them well.

We as teachers of mineralogy and crystallography need to "sell" our sciences better. We seem to have failed in presenting the importance of these subjects in our modern economy, particularly our economy of the last twenty-five years. Each war, each drain on our mineral resources, as well as many normal technical advances, have increased the importance of a knowledge of minerals and crystals in our everyday life. Money is made out of applied mineralogy and crystallography, and because of these applications the world is a better place to live in. These subjects should be given greater weight in our modern engineering curricula which deal with earth materials in any way.

BINOCULAR MICROSCOPE STUDIES IN THE TEACHING OF MINERALOGY AND PETROLOGY[1]

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Introductory courses in mineralogy emphasize the identification of minerals by megascopic means based on crystal form, streak, hardness, cleavage, color, and other diagnostic physical properties combined with simple chemical tests. Optical and X-ray character of minerals is ordinarily studied at the graduate level. Thus in the foundation courses studies are conducted with relatively large, well-chosen hand specimens while at the graduate level precise determinations are made from grain slides or thin sections under high power. Mineral fragments with diameters ranging from about 5 mm. to 1/16 mm. are rarely included in study sets.

It is with these small fragments that the present paper is concerned. Particles in the size range of 5 mm. to 1/16 mm. are important because practically all subsurface geology must be based on them. This is the size range of well samples obtained from standard or rotary drilling methods. From such fragments the specialist in subsurface geology must work out stratigraphy, structure, and problems in sedimentation. For studying these subsurface samples, professional geologists use the binocular microscope with magnification ranging from 9X to 20X.

The binocular microscope is generally lacking from our teaching laboratories for the obvious reason that

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it does not have the precision of the petrographic microscope, and its magnification overlaps the range of the hand lens. On the other hand, the geologist who works with well samples and cores finds little or no use for the hand lens or the petrographic microscope. Present statistics indicate that the majority of our students will find employment in the exploration for petroleum and ground water and that they will be engaged in subsurface studies. In this field, experience has established the usefulness of the binocular microscope.

The existing gap between the study of hand specimens and the precision studies with the petrographic microscope can be bridged at the undergraduate level by the introduction of the binocular microscope as a refinement of megascopic studies. In introductory courses in mineralogy and petrology the student can be taught to recognize the diagnostic features of common minerals and rocks as they appear in fragments down to 1/16 mm. in size. Physical properties of such fragments can be studied with the aid of hardness points, steel forceps, and a streak plate. They may also be removed from the field of the microscope and dropped into chemicals set up in small beakers, or they can be tested before the blowpipe.

Utmost care must be exercised in the selection and preparation of study materials. Pure minerals which are to be studied under the binocular microscope must be identified by exact methods. Every effort should be made to include the common variations of a given mineral. Both fresh and weathered materials should be made available. The study set of minerals should include all of the common rock-forming minerals, the heavy accessory minerals of sedimentary rocks, and the widely distributed ore minerals. Samples can be prepared for study by crushing large pieces, and screening to the desired size. Minerals which tend to form powder that coats the fragments should be washed and dried. The finished sample can be placed in a

container and cataloged.

It is in the study of petrology that the binocular microscope finds its most effective use. Identification of the igneous rocks is accomplished with less difficulty and increased accuracy after the student has studied small fragments of individual rock-forming minerals and learned to identify them by their physical properties. The hand specimen of a granular igneous rock under the binocular microscope presents an aggregate of broken mineral surfaces comparable in size to those studied in mineralogy. The microscope training also assures more effective use of the hand lens in the field.

As an introduction to the subject of sediments and sedimentary rocks, study of a set of weathered igneous rocks of variable composition and texture is very helpful to both student and teacher. Thus decomposition and disintegration can be made real and understandable, and purposefulness is added to the discussion of chemical change and the origin of sediments. In many ways the binocular microscope is more effective in these studies than the polarizing microscope because of the difficulty of preserving clays in thin sections.

Sedimentary rocks lend themselves well to studies with the binocular microscope. The texture of clastic materials in the sand and silt range can be measured quickly and accurately. The composition, shape, and color of fragments can be determined. The composition and approximate amount of the cementing bond, together with the related porosity and permeability, can be studied with varying degrees of accuracy. The essential lithologic features of chemically derived sedimentary rocks can be ascertained from relatively small fragments. Sedimentary rocks made up of shells or shell fragments, and also of plant materials, can be effectively studied. Microfossils in many instances are studied in both direct and transmitted light by

using the higher magnifications of the microscope. The color, approximate texture, degree of induration, and kind of fracture are characters observable in fragments of shale or clay. Study materials of the sedimentary rocks should include a wide variety of lithologic types representative of different environments of deposition.

Only common metamorphic rocks are suitable for study under the binocular microscope. Quartzite, marble, slate, schist, and gneiss are first studied in the hand specimen by megascopic methods and then in small fragments under the microscope. Except for gneiss, these rocks can be accurately identified by examination of small fragments.

It must be emphasized that studies requiring the binocular microscope are not recommended as a substitute for any method currently employed in the teaching of mineralogy and petrology, but rather as an added refinement to megascopic methods. The examination of small fragments of rock-forming minerals under magnifications up to 20X will be found helpful in rock identification, both in the laboratory and in the field. A supervised study of broken particles from 5 mm. to 1/16 mm. in size of the common igneous, sedimentary, and metamorphic rocks will provide a foundation for the correct identification of subsurface rocks recovered from drilling operations. Since many of our students will be engaged, directly or indirectly, in professional studies relating to these bits of rock, it is our responsibility to provide basic studies which require supervised laboratory training in the use of the binocular microscope.

CLEANING MINERAL SPECIMENS

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Although there is no universal way to clean all mineral, rock, or fossil materials, there are nevertheless a few simple inexpensive methods which can be used by anyone to renovate classworn specimens and also prepare field specimens for class use.

Solid, massive, crystalline, or stoutly crystallized specimens that are not soluble in water can easily be cleaned by scrubbing them with soap and water, or better still with water to which a detergent has been added. A brush with stiff bristles and a long handle is superior to soft brushes. An ideal brush is the one used by platers. The brush part measures 1 inch by 5 inches. The bristles are 1 inch long and the overall length of brush and handle is 11½ inches. Of course, soft specimens like talc and selenite should not be brushed too vigorously, nor should any pieces with delicate or filiform crystals be brushed. Wire brushes should seldom be used and then very judiciously to remove rust and weathering stains.

When dirt or clay becomes lodged in crevices or in crystal groups, a round bristle-brush about ¼ to ½ inch in diameter will come in handy. A jet of water supplemented by persistent jabbing of the brush will ultimately clean most specimens of this type.

Any specimens insoluble in water that possess delicate crystals can generally be cleaned satisfactorily by swishing them gently in water, after which they are carefully rinsed and dried. A small soft brush may be used to dislodge any persistently adhering dirt.

Some minerals which are insoluble in water may yet be harmfully affected by water in other ways. Sulfur, for example, is very sensitive to sudden changes of temperature. Immersion in water that is either too hot or too cold may cause it to crack. Some types of chrysocolla may be shattered upon immersion in water and a few varieties of opal are similarly affected.

Certain types of pyrite and marcasite may be very troublesome. While some forms are unaffected by water, other kinds will be affected even by atmospheric moisture. The water will react with the specimen to form sulphuric acid and melanterite (a white or gray powdery material). This action is slowly progressive and may eventually ruin fine specimens. To be on the safe side, it is well to avoid washing pyrite or marcasite with water. If they do accidentally become wet, they should be thoroughly dried with low heat. If the pyrite or marcasite specimens have already started to disintegrate, they should be cleaned with alcohol or carbon tetrachloride, thoroughly dried, and then dipped in clear lacquer.

Halite, chalcanthite, and other water-soluble minerals may be cleaned with organic solvents such as alcohol, carbon tetrachloride, or benzene. If carbon tetrachloride is used, avoid prolonged inhalation of the fumes.

Soft, pulverulent minerals (chalk, kaolin, etc.) and those consisting of filiform crystals (jamesonite), or delicate crystals (aurichalcite, etc.), can best be cleaned by gently blowing off the dirt. If compressed air is available, a low pressure jet may be used to good advantage.

Field excursions frequently produce specimens which are weather-stained, or rust-stained if iron minerals are present. Weathering stains can be removed from most minerals, rocks, and fossils by soaking them in a dilute bleaching solution for fifteen minutes or longer. This solution can be prepared by mixing one

half pint of sodium hypochlorite with a gallon of water. (Do not get the bleaching solution on clothes.) Rust stains may be removed from non-carbonate materials by immersing the specimens in an oxalic acid solution and allowing the solution to come to a boil. This solution can be prepared by dissolving a half ounce of oxalic acid crystals in a gallon of water.

After specimens have been washed with either water or cleaning fluids, it is well to rinse and then dry them carefully with an absorbent towel. The solutions in which specimens have been washed contain a fine suspension of dirt particles. If a film of this dirty solution is allowed to dry on the specimen, a smudge will be left. This will be especially apparent on shining surfaces of substances like obsidian, rock crystal, and calcite.

Silky, asbestiform minerals such as crocidolite, anthophyllite, and some varieties of serpentine and amphibole often become a dirty mass of fibers after repeated handling. A fresh surface can be exposed by gently picking off loose fibers and finally brushing with a dry brush. This method will reduce the size of the specimen, but not seriously if the material has not been too badly handled.

In addition to becoming dirty, softer minerals like talc, selenite, and calcite become abraded by repeated hardness- and acid-testing. Usually these minerals can be renovated without great difficulty. Selenite has one very excellent cleavage; hence, thin cleavage plates may be split off with a knife blade leaving a clean surface. The same procedure may be applied to the micas (muscovite, biotite, phlogopite, etc.). The talc used in hardness sets is usually the foliated kind, from which thin folia can be peeled with the aid of a knife. Calcite, on the other hand, will need a different treatment. It has three good cleavages. If the pieces are large enough, small plates may be cleaved off from each of the six sides. A small tile-setter's hammer is very useful for this purpose.